N89 - 10784

MARS: A WATER-RICH PLANET: Michael H. Carr, U. S. Geological Survey, Menlo Park, CA 94025.

Mars is estimated to have outgassed 0.5-1 km of water, 10-20 bars of CO_2, and 0.1 to 0.3 bars of N_2. These estimates are significantly larger than most previous estimates but are consistent with what is known of the geology of the surface, the composition of the atmosphere and the chemistry and mineralogy of SNC meteorites. Some of the strongest evidence for large amounts of water is from the cratered uplands. In both the northern and southern hemispheres the character of the cratered uplands changes at roughly the 30° latitude. Fretted terrain (Sharp, 1973) and terrain softening (Squyres and Carr, 1986) both suggest the presence of significant amounts of ice within 2 km of the surface at the higher latitudes. In the fretted terrain, presence of abundant ground ice is suggested by its latitudinal distribution, the mobility of debris flows, the presence of closed depressions, and tunneling (Sharp, 1973; Lucchitta, 1984, Squyres, 1978). Terrain softening is best explained by the presence of ice near the surface in sufficient quantities to reduce the effective viscosity of the near-surface materials. Extreme softening in the 30-55° latitude band and less softening in the 55-90° latitudes is consistent with the changing viscosity of ice at the mean temperatures at these latitudes (Lucchitta, 1984). The amount of ice required to change the viscosity and to cause the features of the fretted terrain is unknown but, by analogy with terrestrial features, is believed to be in excess of the porosity, estimated to be at least 10 percent by volume.

Fretted terrain, terrain softening, and debris flows are absent from the cratered uplands at low latitudes (<30°). This suggests that ice, or water, have not been present in the near-surface materials in sufficient quantities to affect their mobility since the geologic record emerged 3.8 billion years ago. Talus was produced on steep slopes as within craters, but it has not had the mobility to flow away from the slopes to produce the variety of flow features seen in the 30-55° latitude bands. Although the surface materials have not flowed, the branching valley networks provide convincing evidence for the presence of groundwater, at least during the early history of the planet. The presence of the networks, coupled with the lack of flow of the near-surface materials, suggests that the water was interstitial, that is, it was present in amounts less than the porosity. Thus, as early as when the geologic record emerged 3.8 billion years ago, a latitudinal contrast had developed between the water content of the near surface materials at high and low latitudes. At high latitudes water was present in amounts that exceeded the porosity; at low latitudes water was present in amounts less than the porosity.

The deep megaregolith has a substantial water-holding capacity (Carr, 1979; Clifford, 1981), the difficulty is knowing the extent to which the capacity is filled. Many of the large outflow channels may have formed through eruption of groundwater under high pressure from the megaregolith beneath the permafrost, which is estimated to have been about 1 km thick. (Carr, 1979). A lower limit on the amount of water involved in formation of the outflow channels can be derived by assuming that the volume of water that flowed through the channels had to be at least as large as the volume of materials eroded to form the channels. This is equivalent to assuming that all the water that flowed through the channels carried the maximum sediment load (Komar, 1980). The total volume eroded to form the circum-Chryse channels is estimated to be 5 x 10^6 km^3, or 35 meters averaged over the entire planet. The area over which the megaregolith was drained to form these channels is unknown but reasonable limits are the summit of the Tharsis ridge to the west, the center of the Tempe plateau to the north, and to the south and east the limits of chaotic terrain. This area is 1.6 x 10^7 km^2 or roughly one tenth of the planet's surface. If we further assume that the water content of the megaregolith in this region was no different from that in other parts of the planet then we conclude that the megaregolith, below one 1 km, planet-wide, contained no less than 350 meters of water. Implicit in this assumption is that the outflow channels are located in the Chryse region not because the megaregolith here contained more water, but because relief was present to create the hydrostatic head needed to drive the water through the permfrost cap to the surface. The assumption of a generally uniform distribution of water in the surface is supported by the uniform distribution of valley networks in the cratered uplands (Clow and Carr, 1981). To the 350 meters must be added the 50-100 meters estimated to be present in the upper 1 km of the cratered uplands at high latitudes, to give a total inventory of 400-450 meters. This is a conservative number in that the assumption that the volume of water that flowed through the cirum-Chryse outflow channels equals the volume of the channels is very conservative. Moreover the megaregolith is unlikely to have been drained dry in the process of making the channels. Finally, the 400-450 meters represents only unbound water. Significant amounts of water may be bound in weathered debris and in primary minerals. In excess of 500 meters of water is thus believed to have been outgassed from the planet.

As indicated above, the contrast between high and low latitudes had already been partly established when the impact rates declined around 3.8 billion years ago, with the near-surface materials containing less water than those at high latitudes. After the impact rates declined, depletion of the low latitudes continued by groundwater seepage, formation of floods and simple diffusion. That lost during large floods appears to have mostly pooled in low-lying areas at high latitudes where numerous features that have been attributed to the presence of ground ice are observed (Carr and Schaber, 1977; Rossbacher and Judson, 1981; Lucchitta, 1981). That lost through formation of valley networks and by diffusion may be presently in the polar layered deposits. Since the impact rates declined much of the surface has been overplated by water-poor, mantle-derived volcanics of which we have representated in the SNC meteorites.

Outgassing of over 0.5 km of water is consistent with the geochemical evidence. Low water inventories estimated by Anders and Owen (1977) and Rasol and LeSergeant (1977) were based on the assumptions that all the argon outgassed from Mars is still present in the atmosphere, and that the ratio of the non-radiogenic noble gases to other volatiles on Mars is the same as on Earth. Both these assumptions are now suspect. Noble gases could have been lost from the early atmopshere by impact erosion or hydrodynamic escape, and the noble/non-noble gas ratio is demonstrably not the same on Venus as on Earth, so the assumption that Mars should be the same as the Earth is questionable. Although nitrogen isotopes may be used successfully to derive the nitrogen content of the early atmosphere (McElroy and Yung 1976), their utitilty in deriving the total volatile inventory is more doubtful because of uncertainties in the amounts of nitrogen fixed in the ground. SNC meteorites suggest that Mars is richer than the Earth in moderately volatile elements (Dreibus and Wanke, 1984), as is expected from models of planetary accretion (Lewis, 1974), but they contain little evidence on abundances of the more volatile atmosphilic elements.

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